Property Measurements of Higgs-like Single Resonance at LHC

MELA and Spin Hypothesis Separation

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On behalf of CMS++

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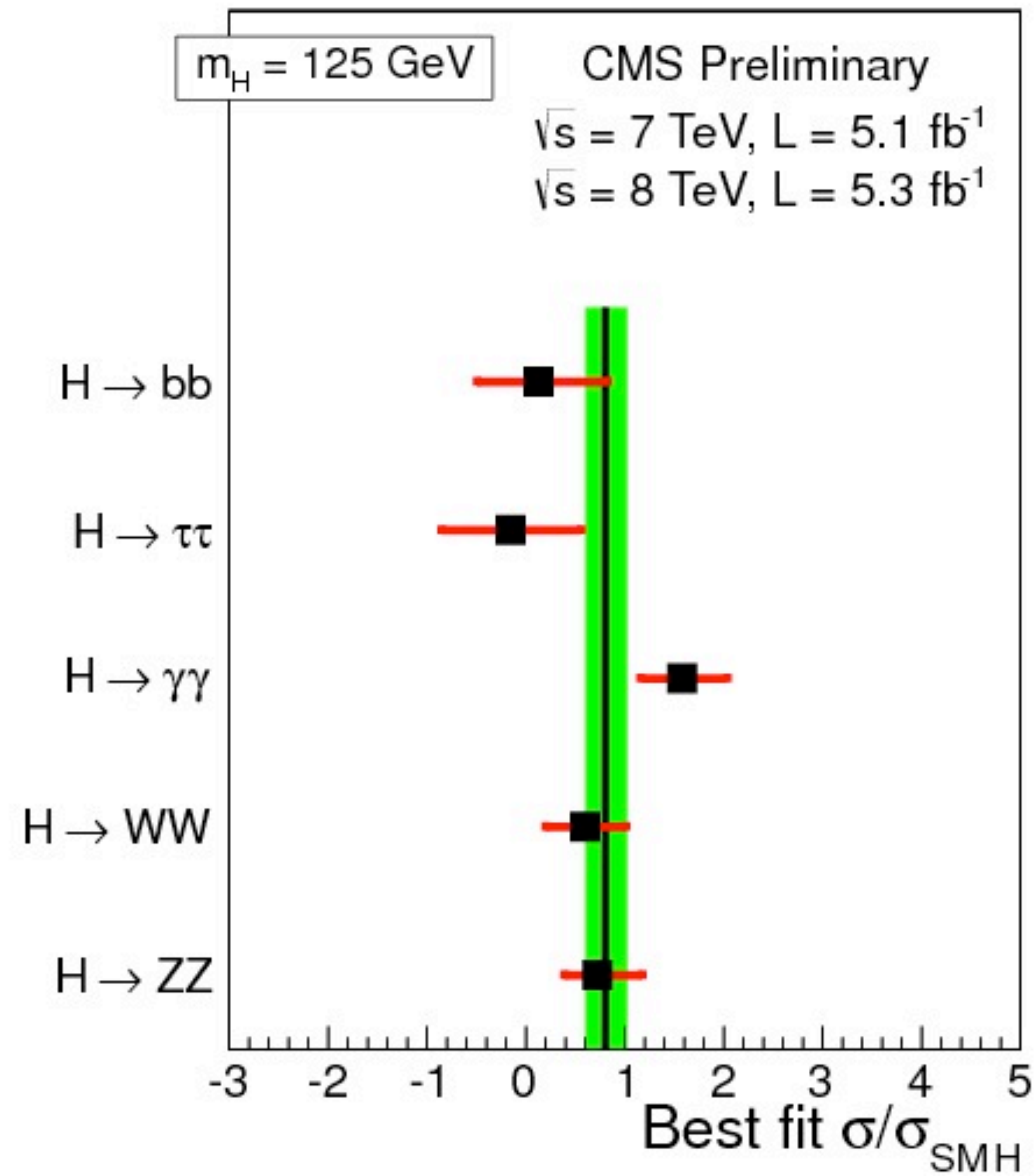
Motivation

- LHC has observed a single resonance with mass ~ 125 GeV
  - Primarily driven in di-boson channels
- The spin/parity measurement is a crucial step to understand the resonance and its interactions with SM particles
  - Given the large contribution in γγ, the spin-1 hypothesis is not favored
  - Among all other possibilities, consider the following interesting spin/parity hypotheses
    - Scalar: 0+
    - Pseudo-scalar: 0-
    - Tensor 2+



Outline

- An update of previous report by Nhan Tran
  - https://indico.cern.ch/contributionDisplay.py?contribId=34&confId=162621
- Brief reminder of the general pp→X→VV interactions and angular analysis
  - MC generator used to simulate the pp→X→VV interactions
- The Matrix Element Likelihood Analysis in X→ZZ→4l
  - Impact on the H→ZZ→4l search
  - The spin/parity hypothesis test in the X→ZZ→4l
- The spin/parity hypothesis test in the X→WW→(lν)(lν)
- Summary and conclusions

Describe $pp \to X \to VV$ Interactions

X→VV Amplitude for Spin-0

- A general amplitude in terms of polarization vectors

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} M_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right)$$

- This allows us to rewrite it in the form of the helicity amplitudes, which later can be connected to the experimental angular analysis

$$A_{00} = -\frac{M_X^2}{v}\left(a_1 x + a_2 \frac{M_{V_1} M_{V_2}}{M_X^2}(x^2-1)\right)$$

$$A_{\pm\pm} = +\frac{M_X^2}{v}\left(a_1 \pm i a_3 \frac{M_{V_1} M_{V_2}}{M_X^2}\sqrt{x^2-1}\right) \quad \Leftarrow \quad x = \frac{M_X^2 - M_{V_1}^2 - M_{V_2}^2}{2 M_{V_1} M_{V_2}}$$

- Fo the SM Higgs, a1 = 1

X→VV Amplitude for Spin-2

- General amplitude in terms of both field strength tensor and polarization vectors

$$\begin{aligned}
A = \frac{e_1^{*\mu} e_2^{*\nu}}{\Lambda} \Big[& c_1\, t_{\mu\nu}(q_1 q_2) + c_2\, g_{\mu\nu} t_{\alpha\beta}(q_1-q_2)^\alpha (q_1-q_2)^\beta \\
& + \frac{c_3\, t_{\alpha\beta}}{M_X^2} q_{2\mu} q_{1\nu} (q_1-q_2)^\alpha (q_1-q_2)^\beta + 2c_4 \left(t_{\mu\alpha} q_{1\nu} q_2^\alpha + t_{\nu\alpha} q_{2\mu} q_1^\alpha \right) \\
& + \frac{c_5 t_{\alpha\beta}}{M_X^2} (q_1-q_2)^\alpha (q_1-q_2)^\beta \epsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma + c_6 t^{\alpha\beta} (q_1-q_2)_\beta \epsilon_{\mu\nu\alpha\rho} q^\rho \\
& + \frac{c_7 t^{\alpha\beta}}{M_X^2} (q_1-q_2)_\beta \left(\epsilon_{\alpha\mu\rho\sigma} q^\rho (q_1-q_2)^\sigma q_\nu + \epsilon_{\alpha\nu\rho\sigma} q^\rho (q_1-q_2)^\sigma q_\mu \right) \Big]
\end{aligned}$$

2^+ CP, 2^- $\not{CP}$ (terms c_1–c_4)

2^+ $\not{CP}$, 2^- CP (terms c_5–c_7)

- Similarly we can write down helicity amplitudes to connect with the experimental angular analysis

$$A_{00} = \frac{M_X^4}{M_V^2 \sqrt{6}\Lambda} \left[(1+\beta^2) \left(\frac{c_1}{8} - \frac{c_2}{2}\beta^2 \right) - \beta^2 \left(\frac{c_3}{2}\beta^2 - c_4 \right) \right]$$

$$A_{\pm\pm} = \frac{M_X^2}{\sqrt{6}\Lambda} \left[\frac{c_1}{4} (1+\beta^2) + 2c_2\beta^2 \pm i\beta (c_5\beta^2 - 2c_6) \right]$$

$$A_{\pm 0} \equiv A_{0\pm} = \frac{M_X^3}{M_V \sqrt{2}\Lambda} \left[\frac{c_1}{8} (1+\beta^2) + \frac{c_4}{2}\beta^2 \mp i\beta \frac{(c_6 + c_7\beta^2)}{2} \right]$$

$$A_{+-} \equiv A_{-+} = \frac{M_X^2}{4\Lambda} c_1 (1+\beta^2)$$

- Examples include Z’, KK gluons, RS graviton, etc.
  - For the RS graviton we consider the minimal coupling case where g1=g5=1

Angular Analysis

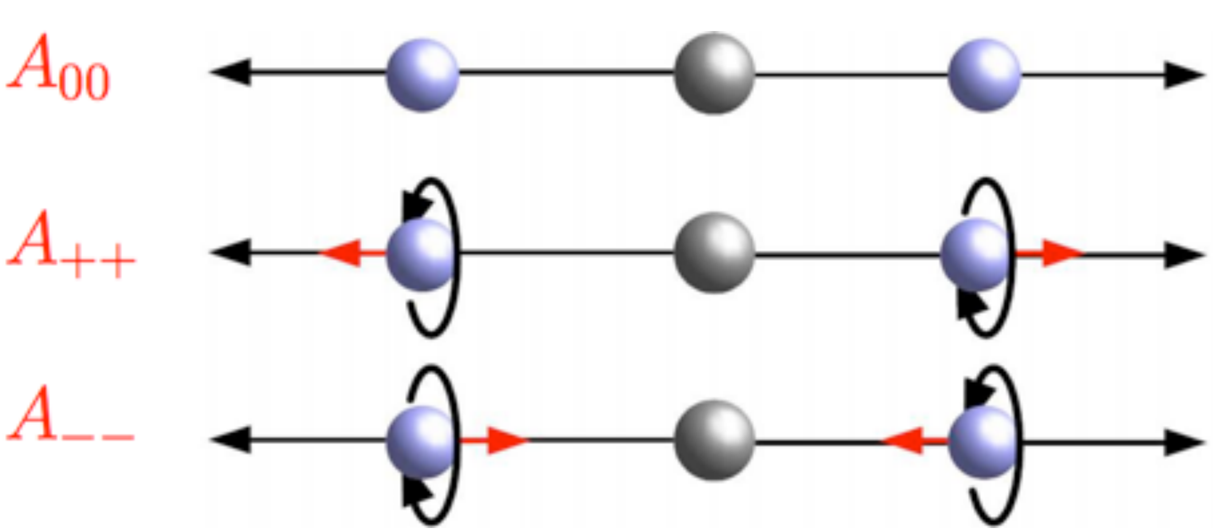
- The helicity amplitudes can be measured from angular analysis

$$d\sigma \propto \sum_{\chi,\mu,\tau} \left|\sum_{\lambda,m} A_{ab}(\{\Omega\})\right|^2$$

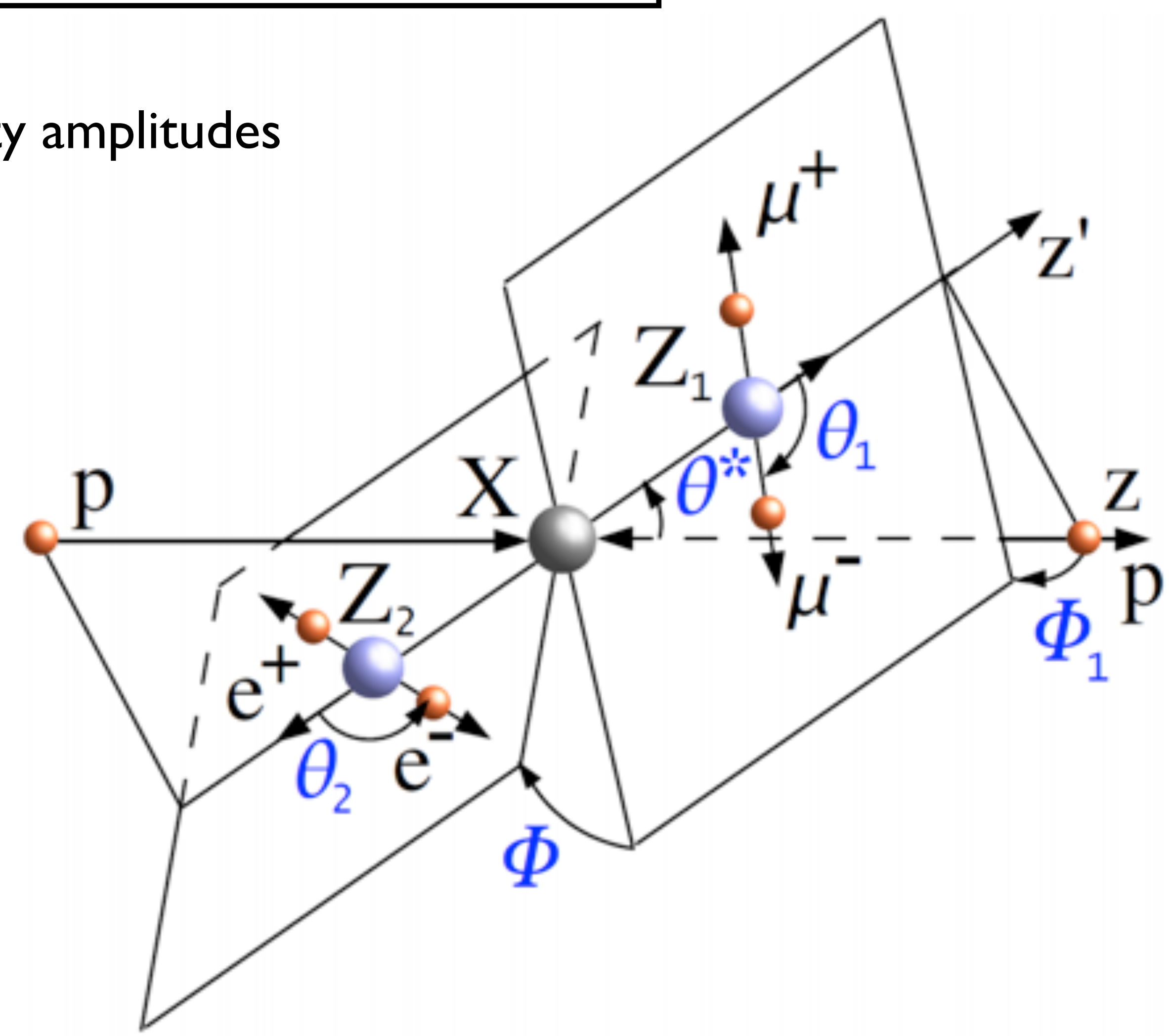
$$A_{ab} \propto \quad D^{J*}_{\chi_1-\chi_2,m}(\Omega^*)B_{\chi_1\chi_2} \times D^{J*}_{m,\lambda_1-\lambda_2}(\Omega)A_{\lambda_1\lambda_2}$$

$$\times D^{s_1*}_{\lambda_1,\mu_1-\mu_2}(\Omega_1)T(\mu_1,\mu_2) \times D^{s_2*}_{\lambda_2,\tau_1-\tau_2}(\Omega_2)W(\tau_1,\tau_2)$$

- For example, a Higgs like spin 0 resonance has 3 helicity amplitudes



Need only 5 angles $\{\theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$
to fully describe the production/decay



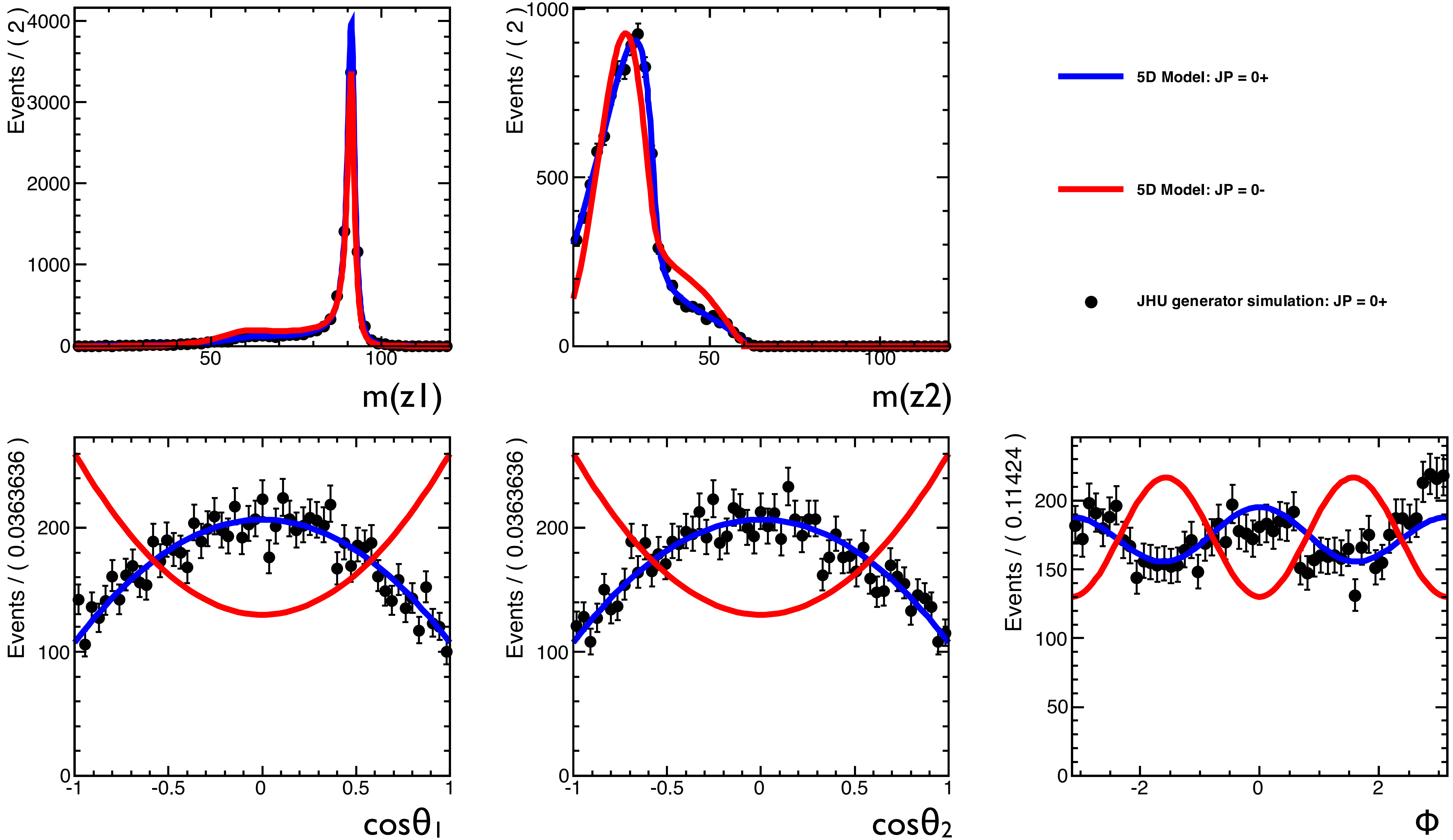
- Detailed expressions for the spin 1 and spin 2 can be found in the reference *PhysRevD.81.075022*

The JHU Generator

- A MC program developed to simulate production and decay of $X \to VV$ with X spin <= 2
  - $X \to ZZ \to$ 4l, 2l2τ, 2l2ν, 2l2q
  - $X \to WW \to$ 2l2ν, lντν, lνqq
  - $X \to \gamma\gamma$
- Includes all spin correlations and all possible couplings
  - Inputs are general dimensionless couplings - calculates matrix elements
- For the production of X, both gg and qq are considered
- Output in LHE format; e.g. can interface to Pythia for hadronization
- All code publicly available: www.pha.jhu.edu/spin

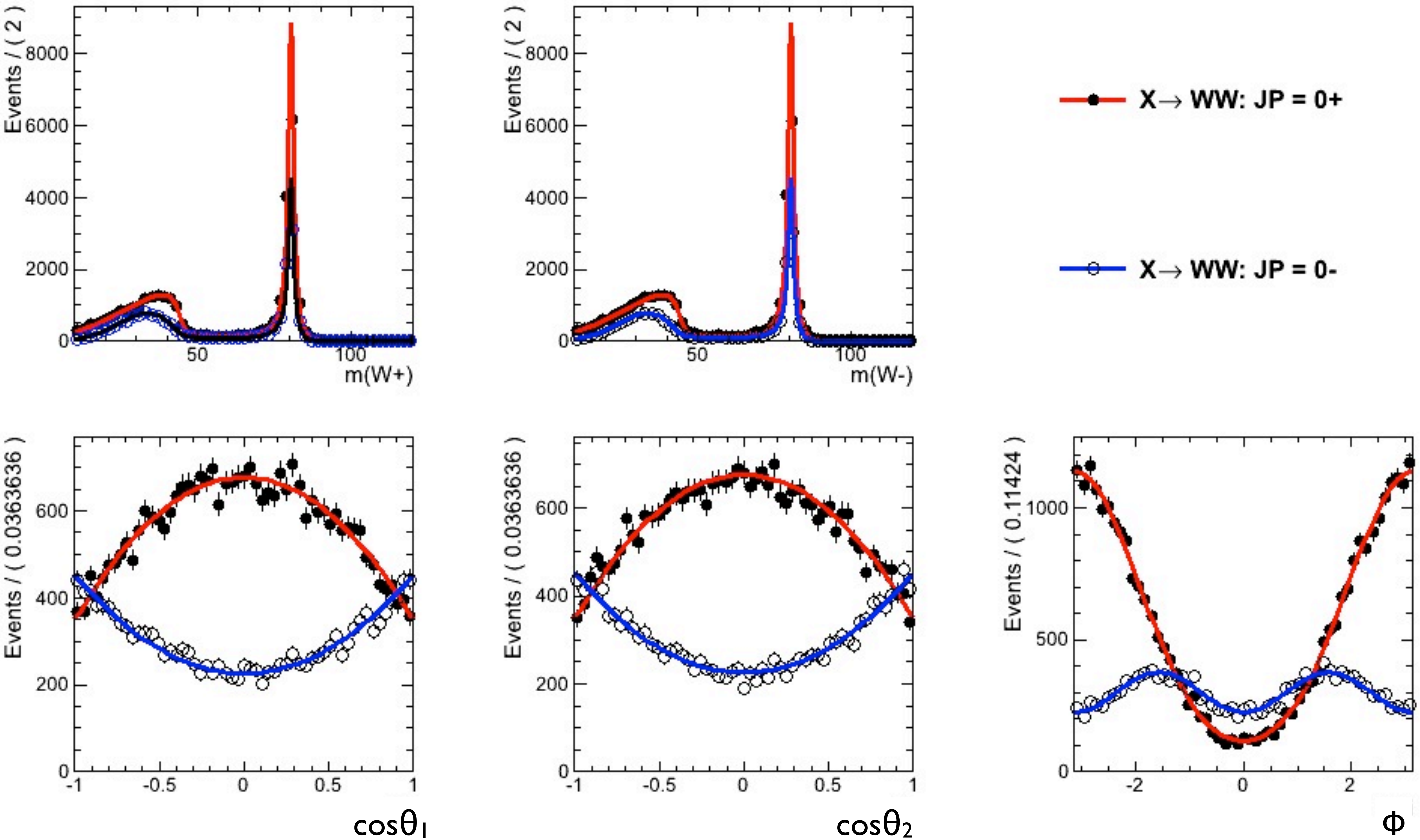
Generator Validation (X→ZZ Spin 0)

- In this test mX = 125 GeV



Generator Validation (X→WW Spin 0)

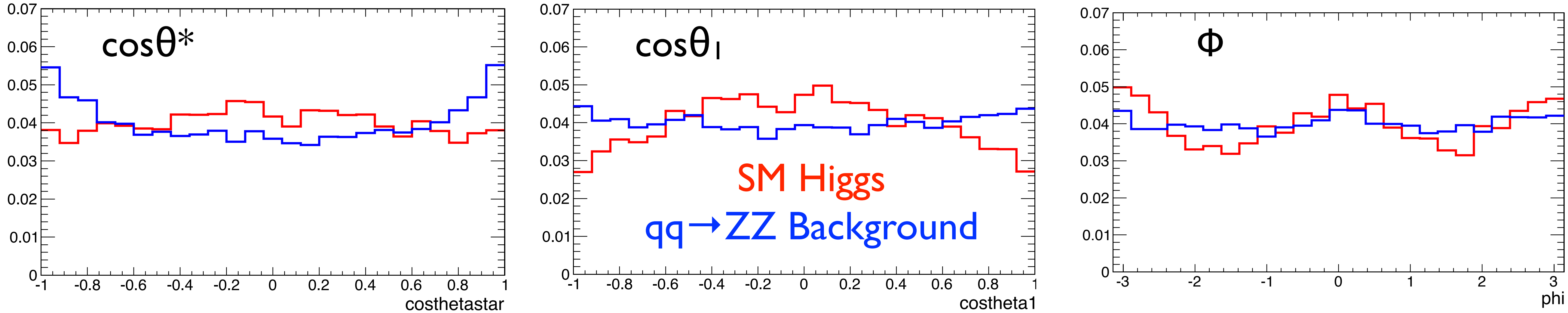
- In this test mX = 125 GeV



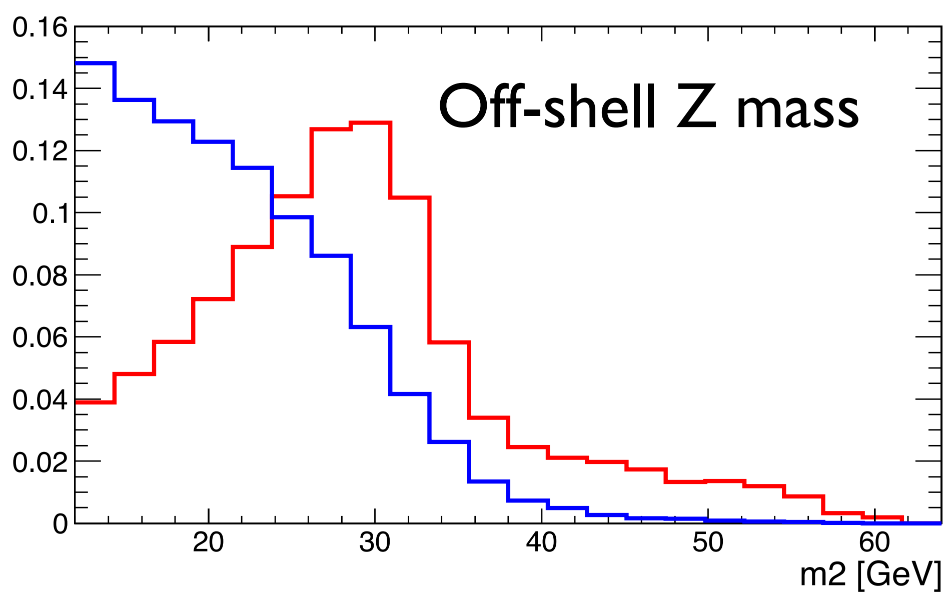
The Matrix Element Likelihood Analysis in ZZ(4l) channel

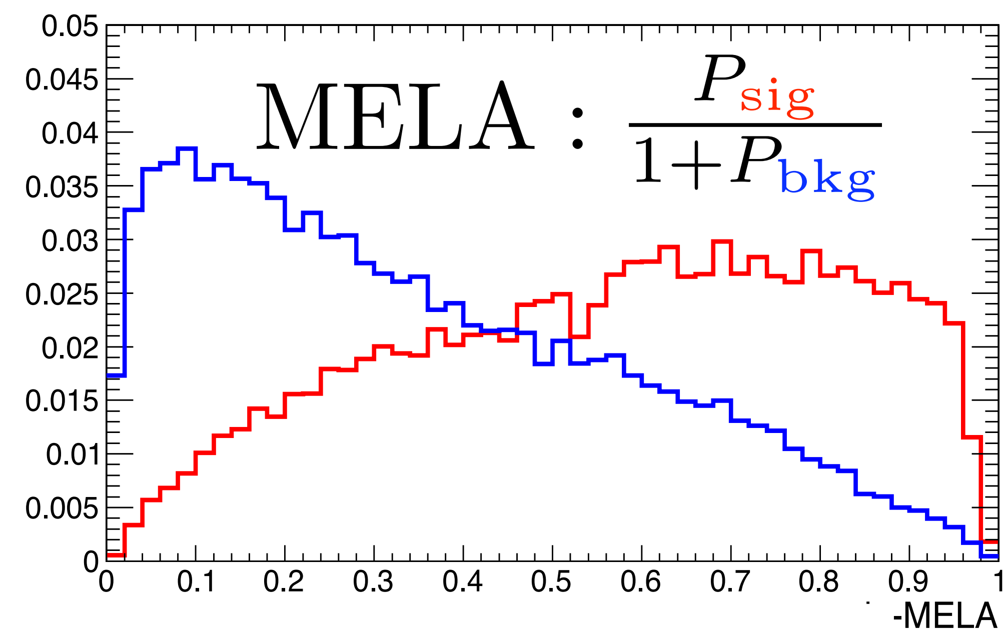
MELA in H→ZZ→4l Search

- The angular variables can be used to distinguish between Higgs signal and SM Background



- We can build analytical likelihoods based on 5 angular variables and 2 on(off)-shell Zmass for sig/bkgd processes and construct a single distinguishing variable "MELA"



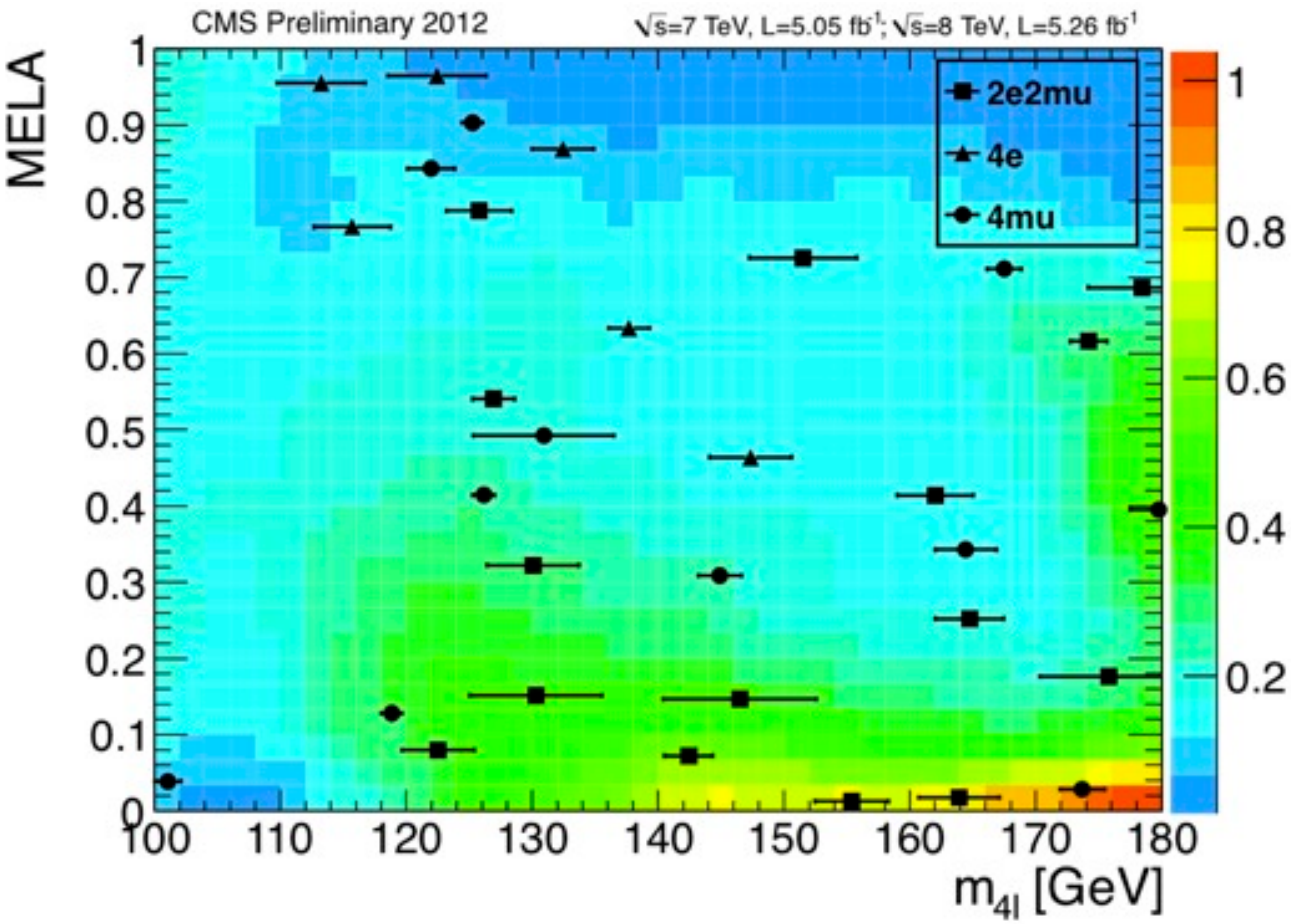


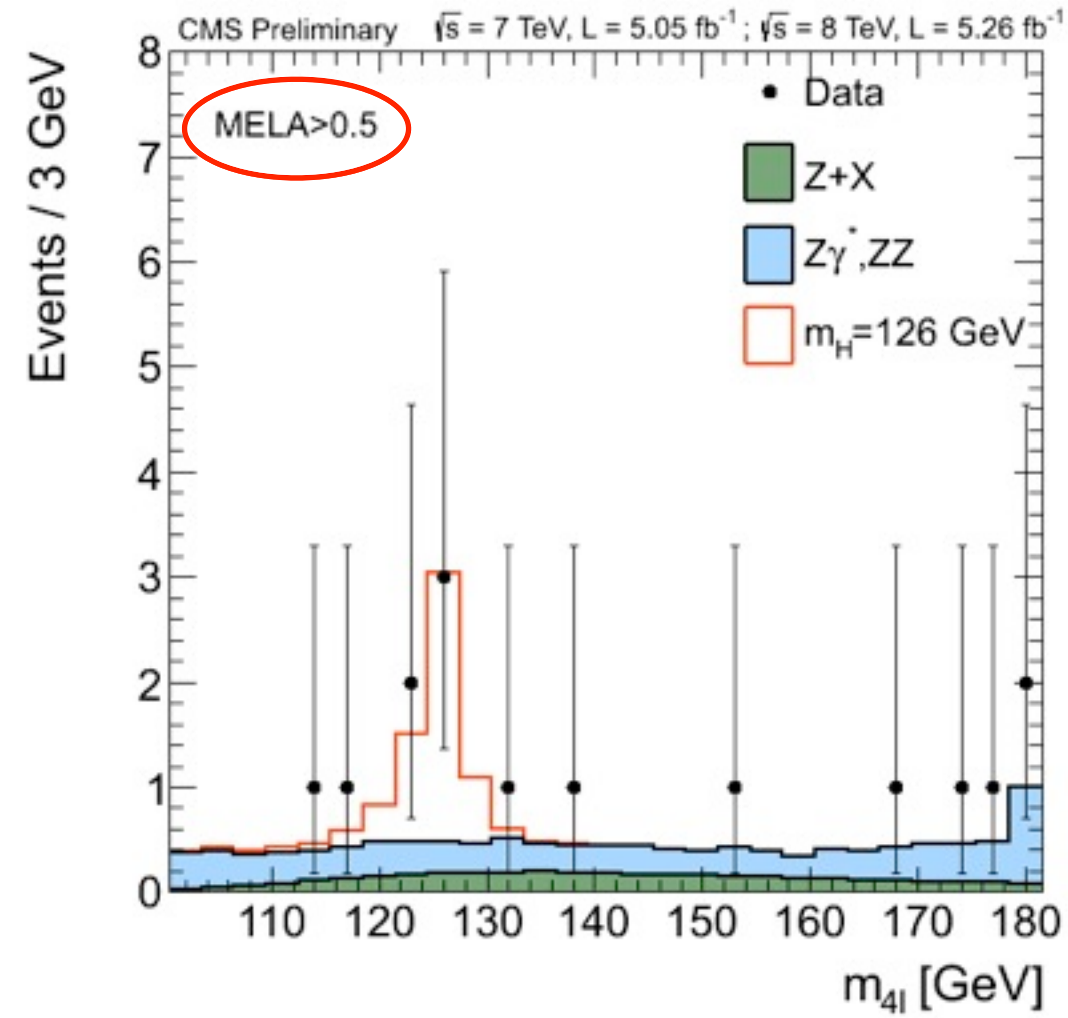
- A toy study using CMS-like analysis shows that using MELA increases the search sensitivity by ~15-30% compared to using only the 4l mass

Reference: arXiv:1108.2274 arXiv:1001.3396)

MELA in CMS H→ZZ→4l

- The CMS HZZ(4l) search uses a 2D template based on [m(4l), MELA]



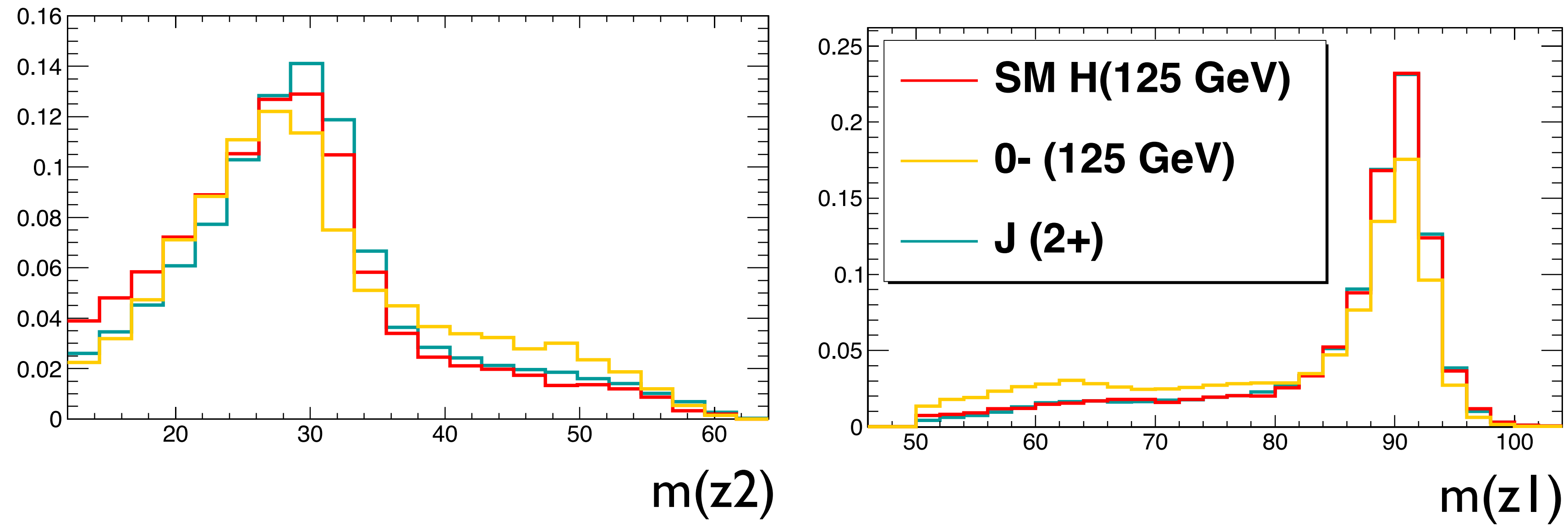


Spin/Parity Hypothesis Separations

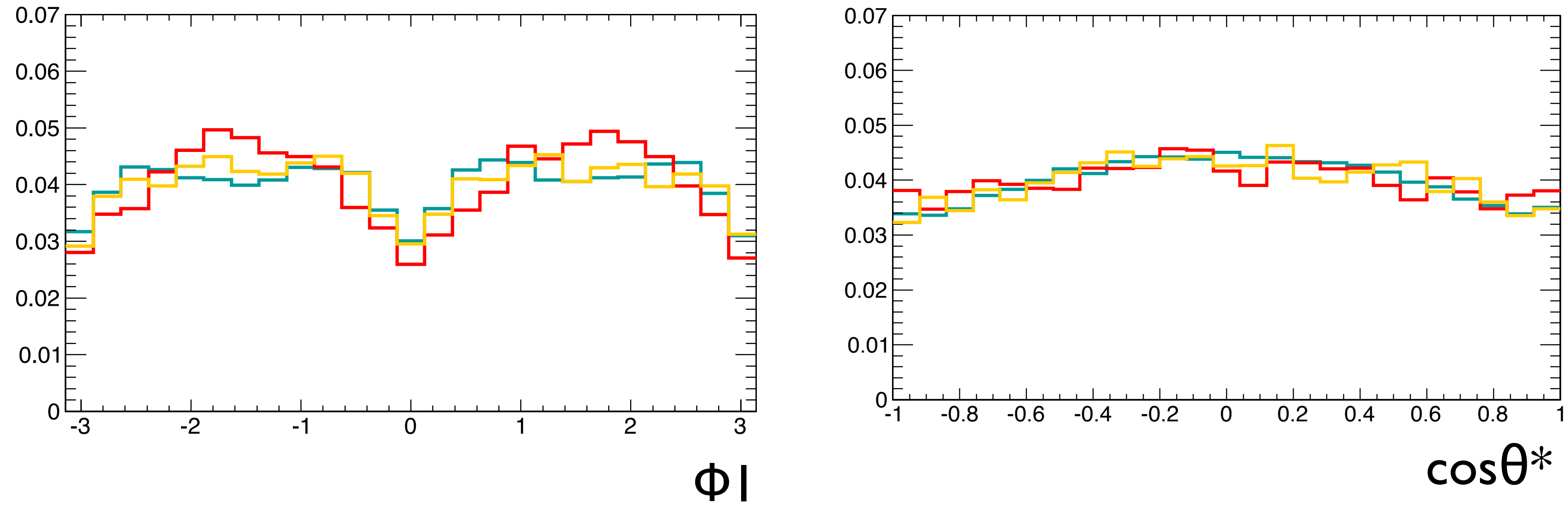
$X \rightarrow ZZ \rightarrow 4l$

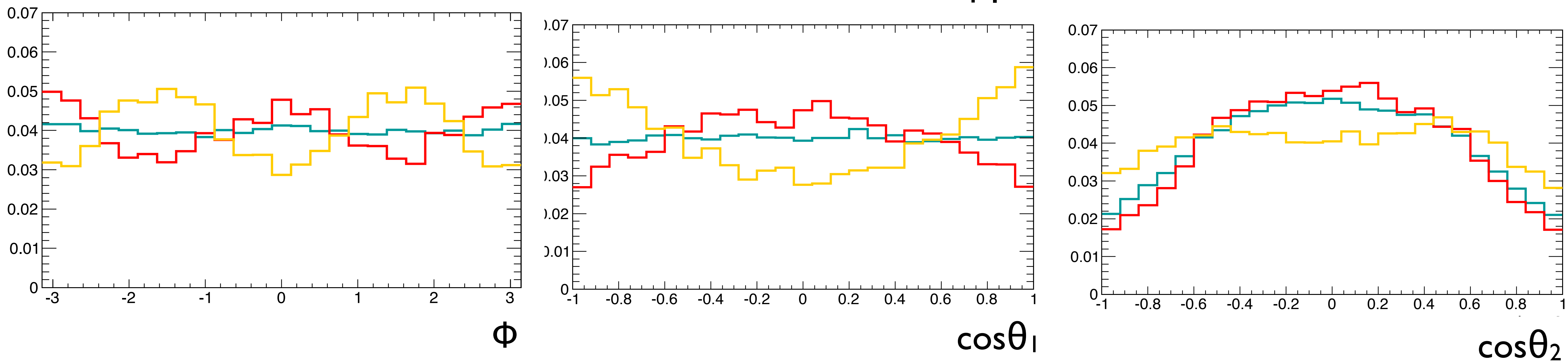
Kinematics for different spin/parity

- The full 7-D variables
  - Good separations between 0+ and 0-



Pseudo-data with CMS like detector resolutions



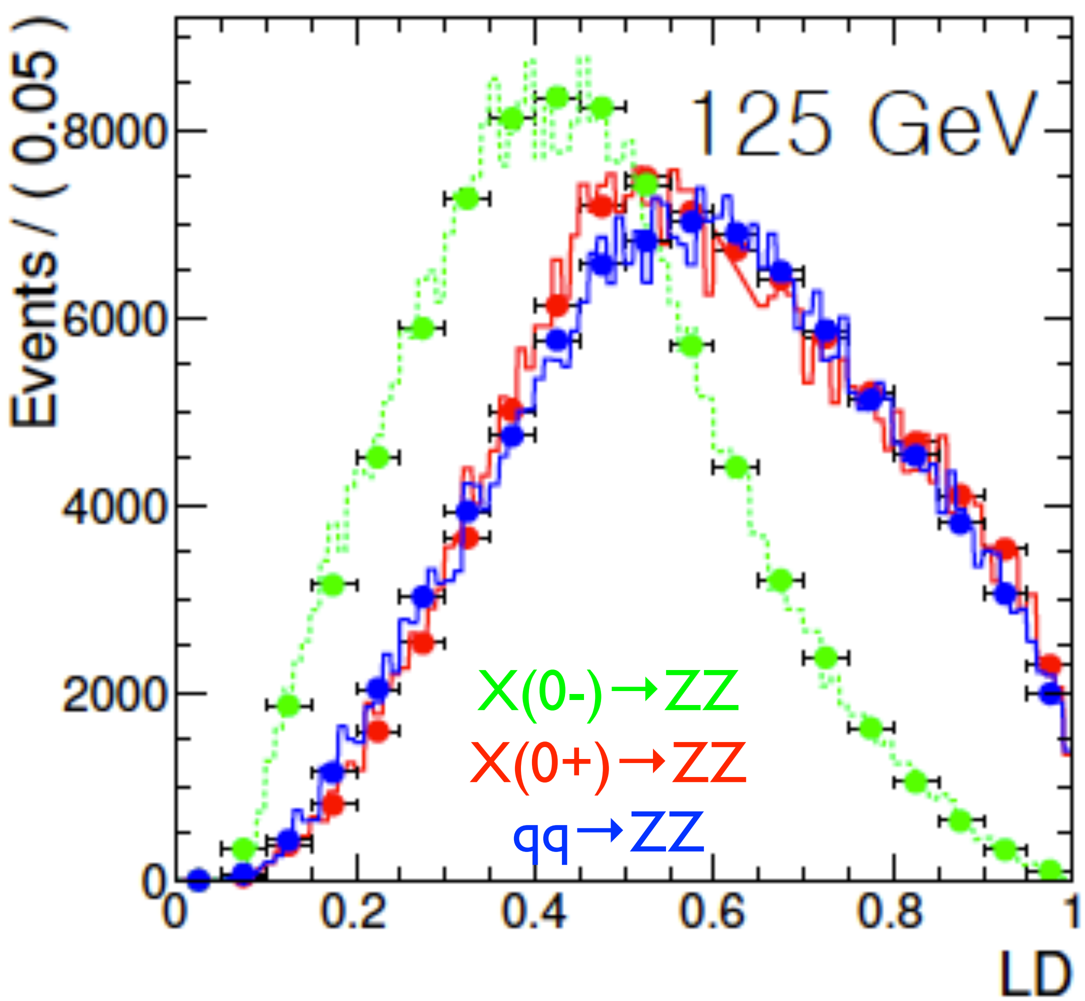


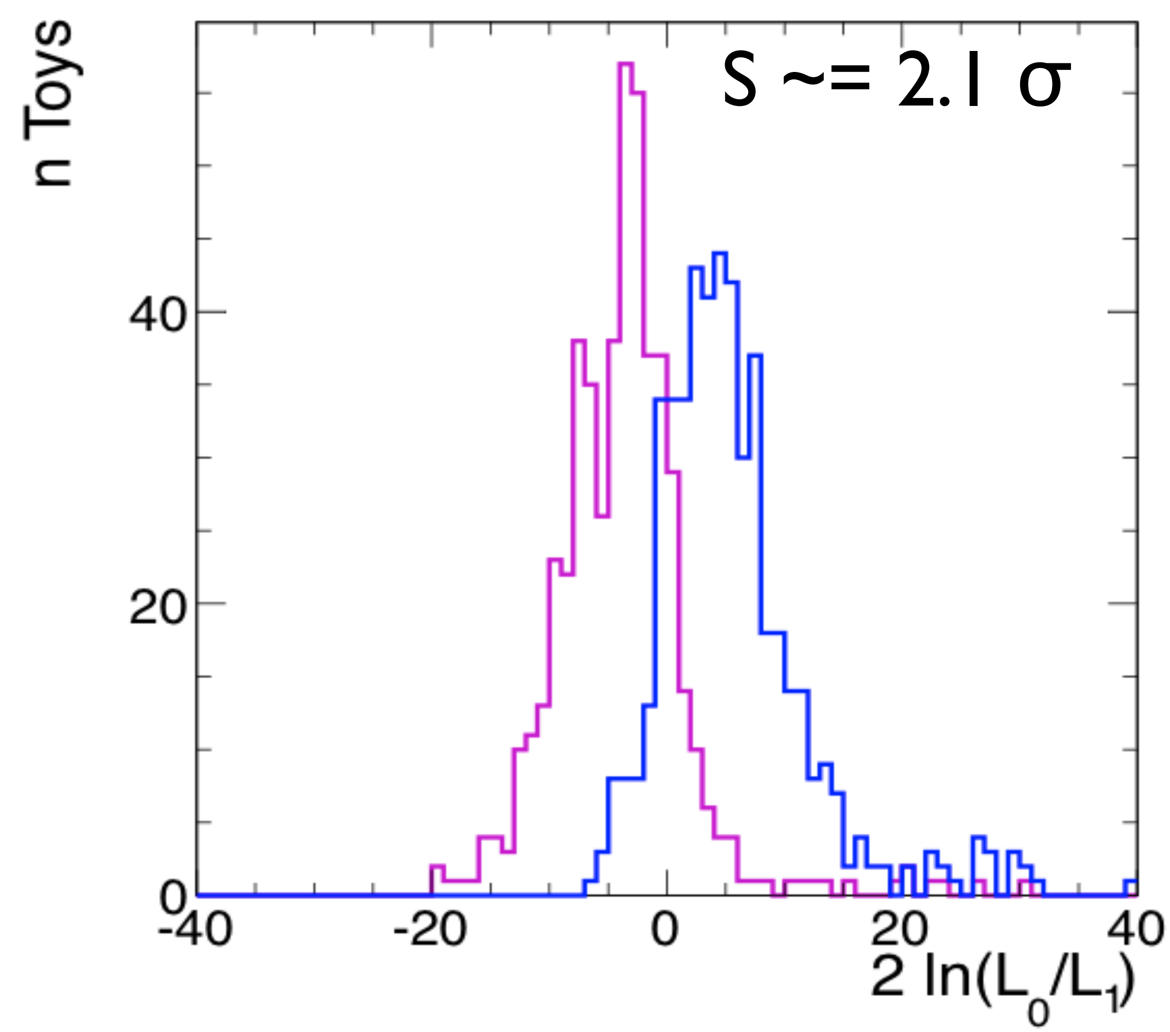
PseudoMELA (0+ vs 0-)

- Construct similar likelihood that distinguishes 0- vs 0+

$$\text{PseudoMELA: } \frac{P_{0+}}{P_{0+}+P_{0-}}$$

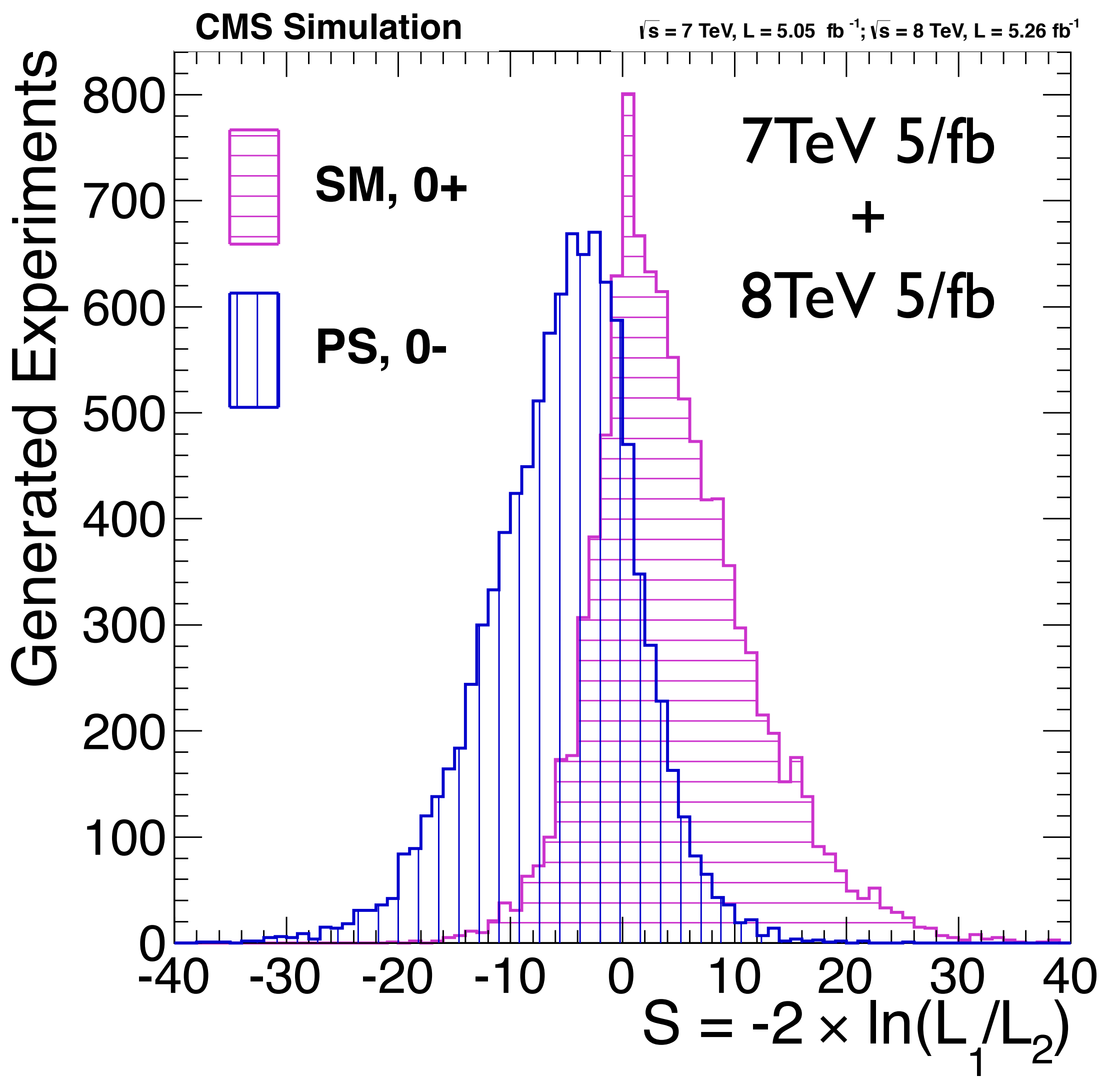
- Using pseduoMELA we expect ~ 2σ separation between 0+ and 0- projected for 20/fb
  - Assume the 0+ and 0- the same signal strength as the SM Higgs
  - For 20/fb, we expect the separation significance ~ 2.1σ

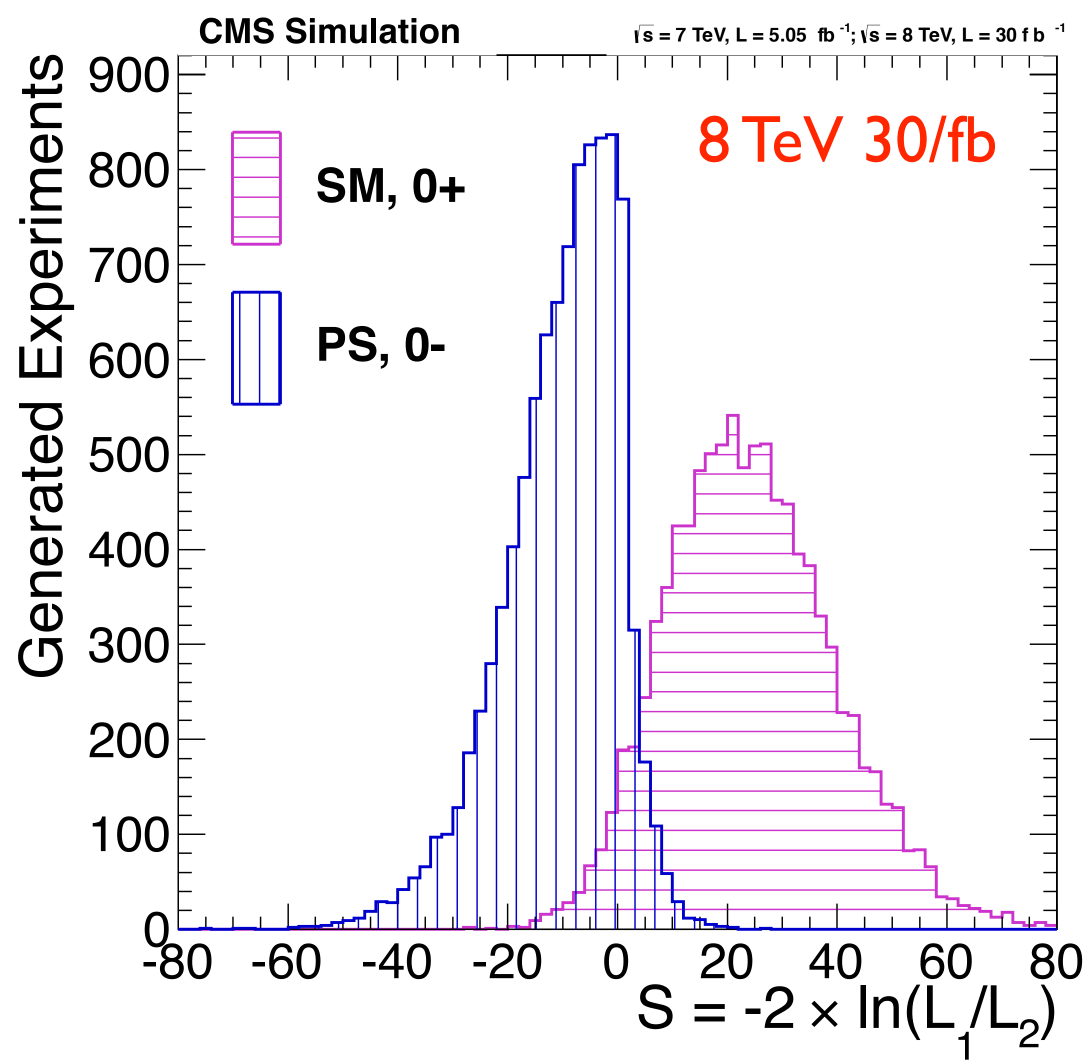




PseudoMELA in CMS

- PseudoMELA is fully implemented in CMS
    - Current status: 1.6 σ expected separation using 5/fb 7 TeV + 5/fb 8 TeV data
    - Projections for 30/fb at 8 TeV: ~3 σ separation



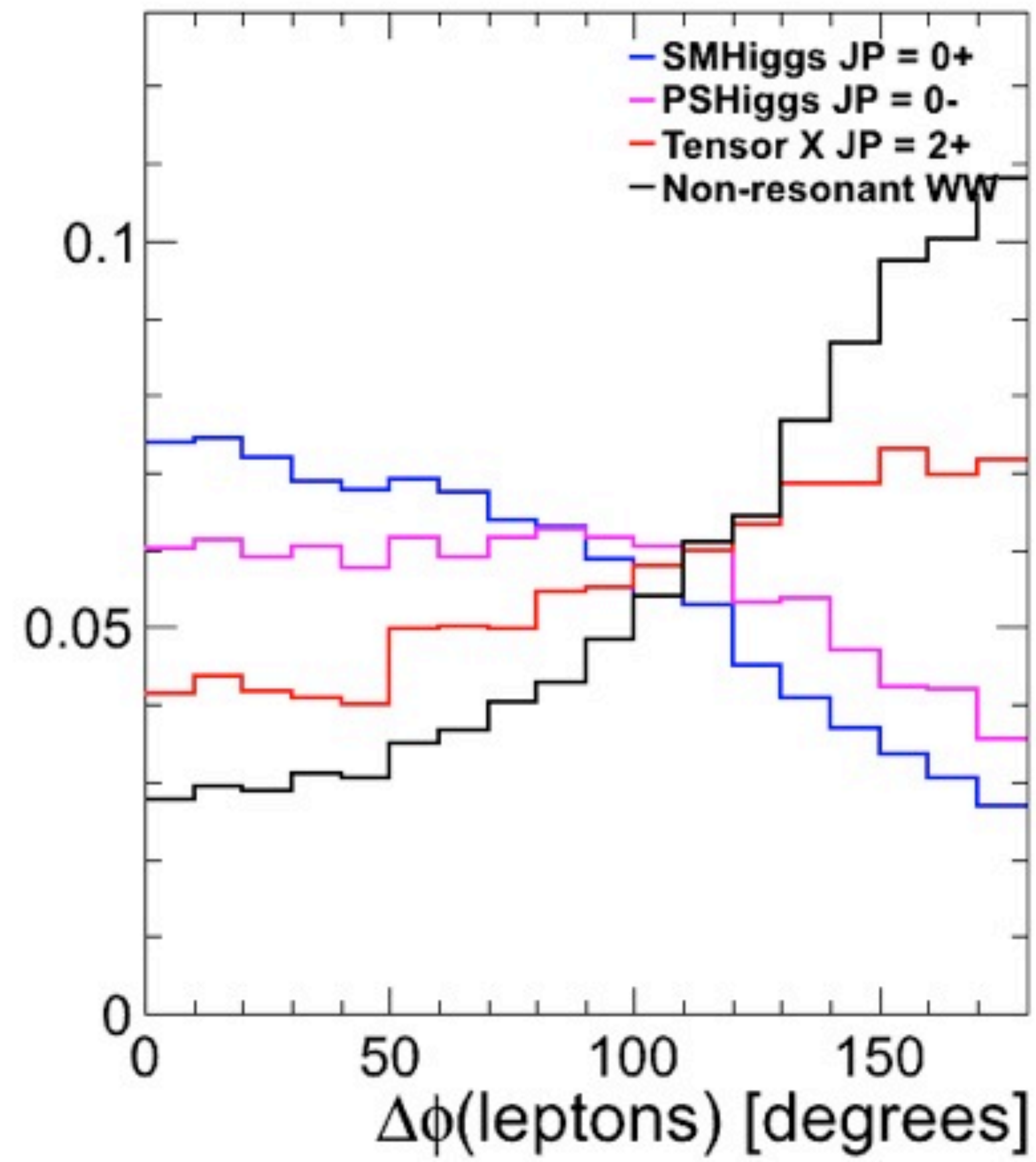


Spin/Parity Hypothesis Separations

$X \to WW \to (l\nu)(l\nu)$

The X→WW Analysis

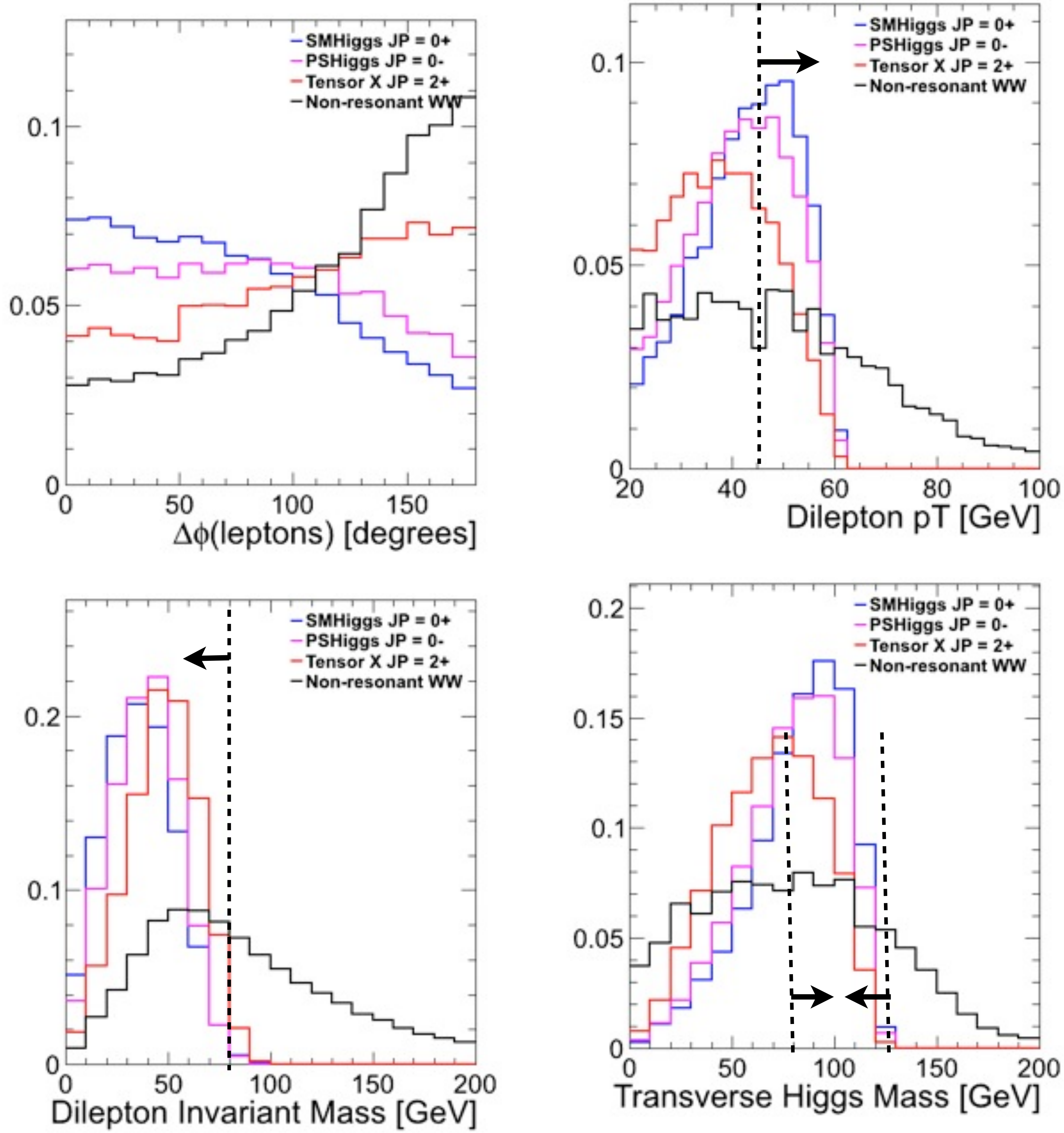
- Due to the missing νs, the WW final state is not fully reconstructible
  - No reconstructed resonance mass
  - The full angular distributions are not available
- Experimental variables can still be used to distinguish different spin/parity
  - For instance the opening angle between the two leptons carry important message
  - See also J.Ellis et al. *arXiv:1202.6660*
- The CMS/ATLAS analyses are optimized for the scalar resonance
  - The selections may not be suitable for the hypothesis tests



For spin-2 we consider the minimal coupling model

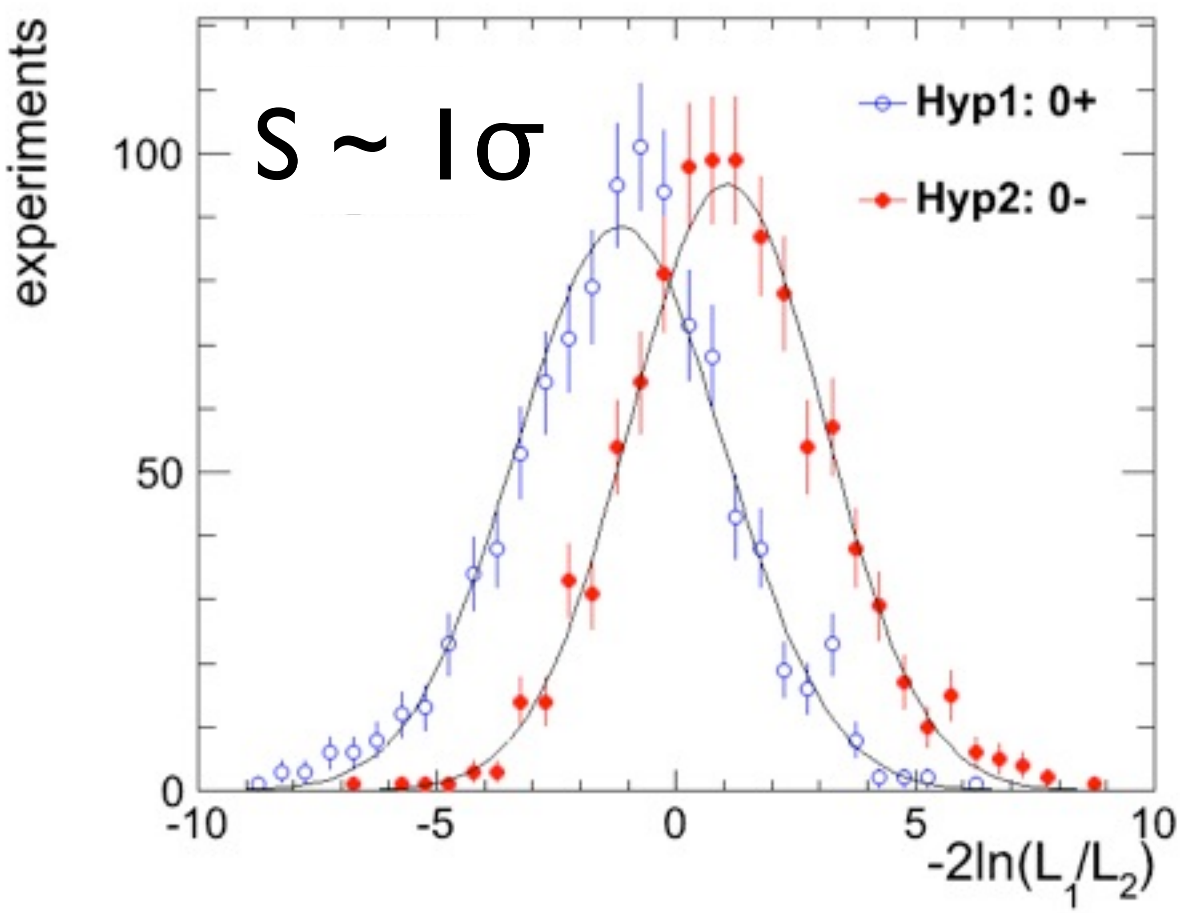
Explore more kinematic observables

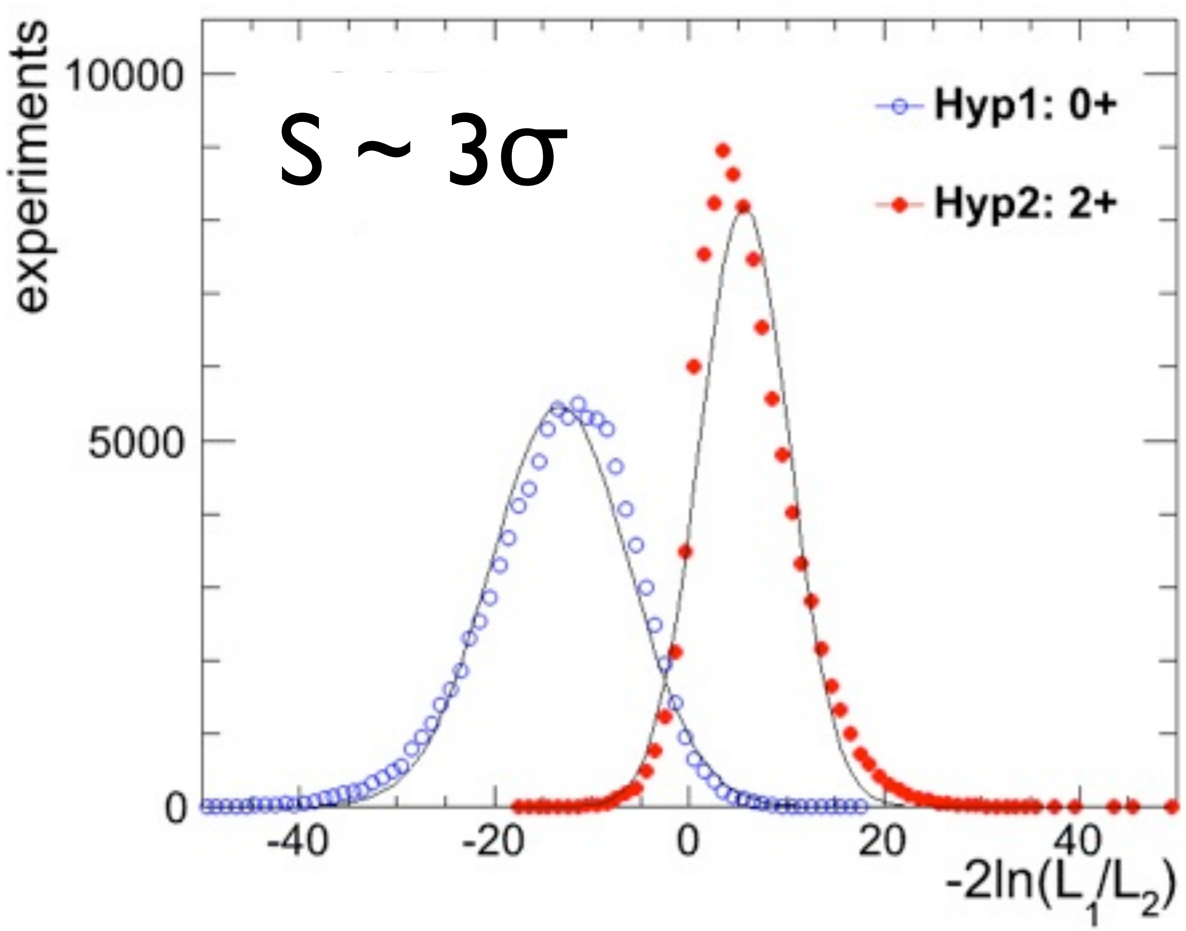
- Select dilepton events with pT[20,10] and within |η|<2.5
  - Plots are normalized by area for the shape comparison
  - Arrows indicate the shape-based analysis cuts in CMS
- For the XWW analysis
  - Use only the purest channel, eμ events with 0 jets
  - Relax cuts on dilepton pT and MET and mT
- For 10/fb at 8 TeV, we expect
  - 25 signal
  - 250 background
    - Assume it is all WW



Hypothesis Separation Results

- Consider an ideal/optimistic scenario
  - Ignore the systematics and and assume the background is all WW
- Use the 2D template based on (mll, mT)
- For 10/fb we project ~1σ separation for 0+ vs 0-, and ~3 σ for 0+ vs 2+
  - The separation between 0+/2+ can reach ~5σ with ~30/fb data in this optimistic case
    - Systematics and other bkgd will degrade the performance. By how much needs future studies.





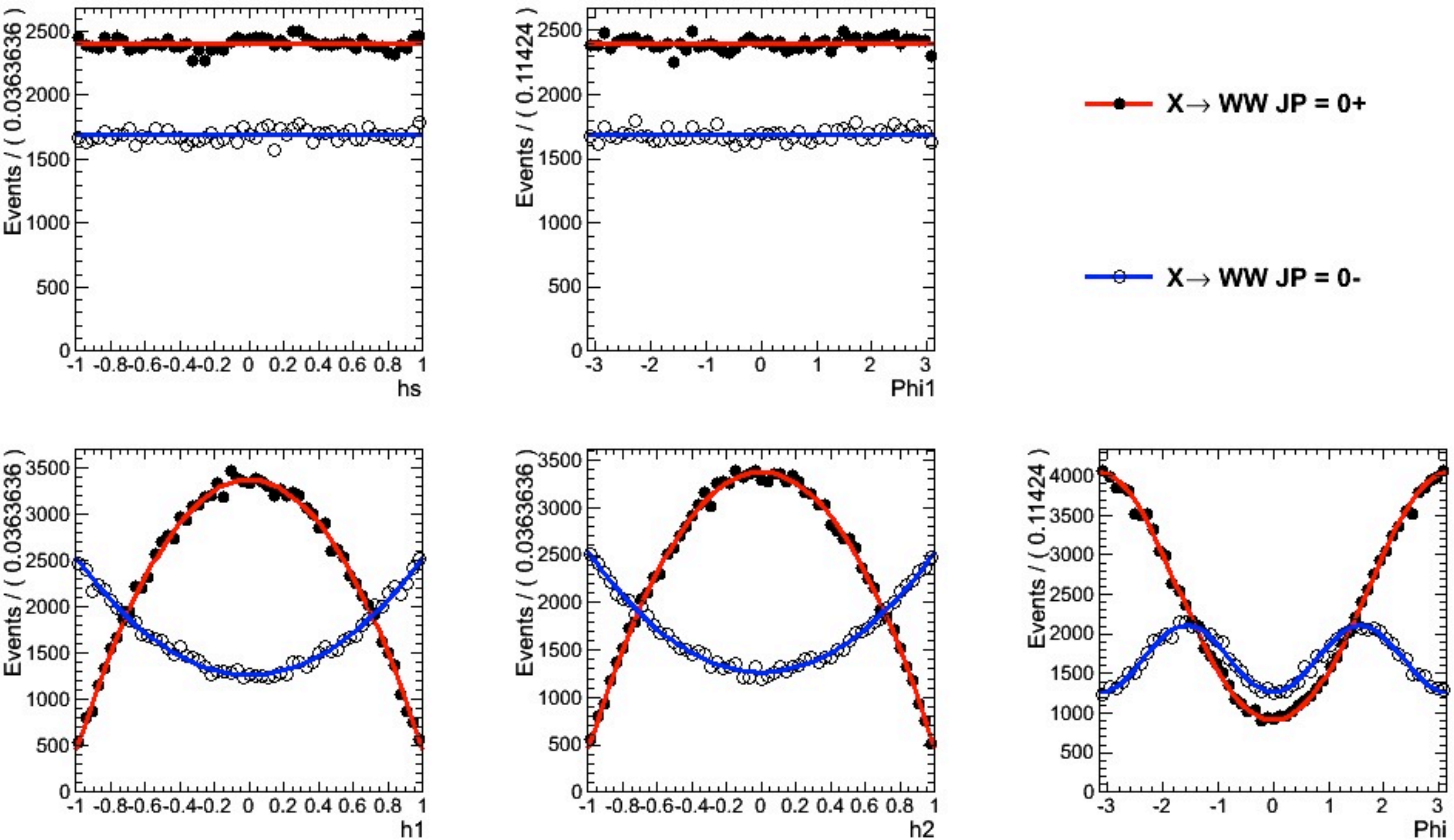
Summary

- An exciting "Higgs-like" resonance has been observed
  - Identifying the resonance's spin and parity is crucial to ping done the nature of this resonance
- We reviewed the model-independent amplitude for $X \to VV \to 4$ fermions interaction as well as a supporting MC generator as a baseline for spin/parity determinations
- We updated the MELA analysis used for both Higgs search and hypothesis separations
  - MELA is used in CMS HZZ(4l) analysis and shown improvement to the Higgs search sensitivity
  - A hypothesis separation based on MELA is also employed in CMS in the HZZ(4l) analysis
    - Expected 0+ vs 0- separation at 1.6 σ with current data, and ~3 σ for 30/fb data
- We introduced similar analysis for the $X \to WW \to (l\nu l\nu)$ channel
  - Using variables (mll, mT) this channel has promising sensitivity of 0+ and 2m+ separations
  - With 30/fb data with ideal condition, we expect ~ 5σ separation
    - WARNING: consider only GEN quantities and ignore non-WW background or systematics
    - We look forward to a realistic analysis from LHC

Backup slides

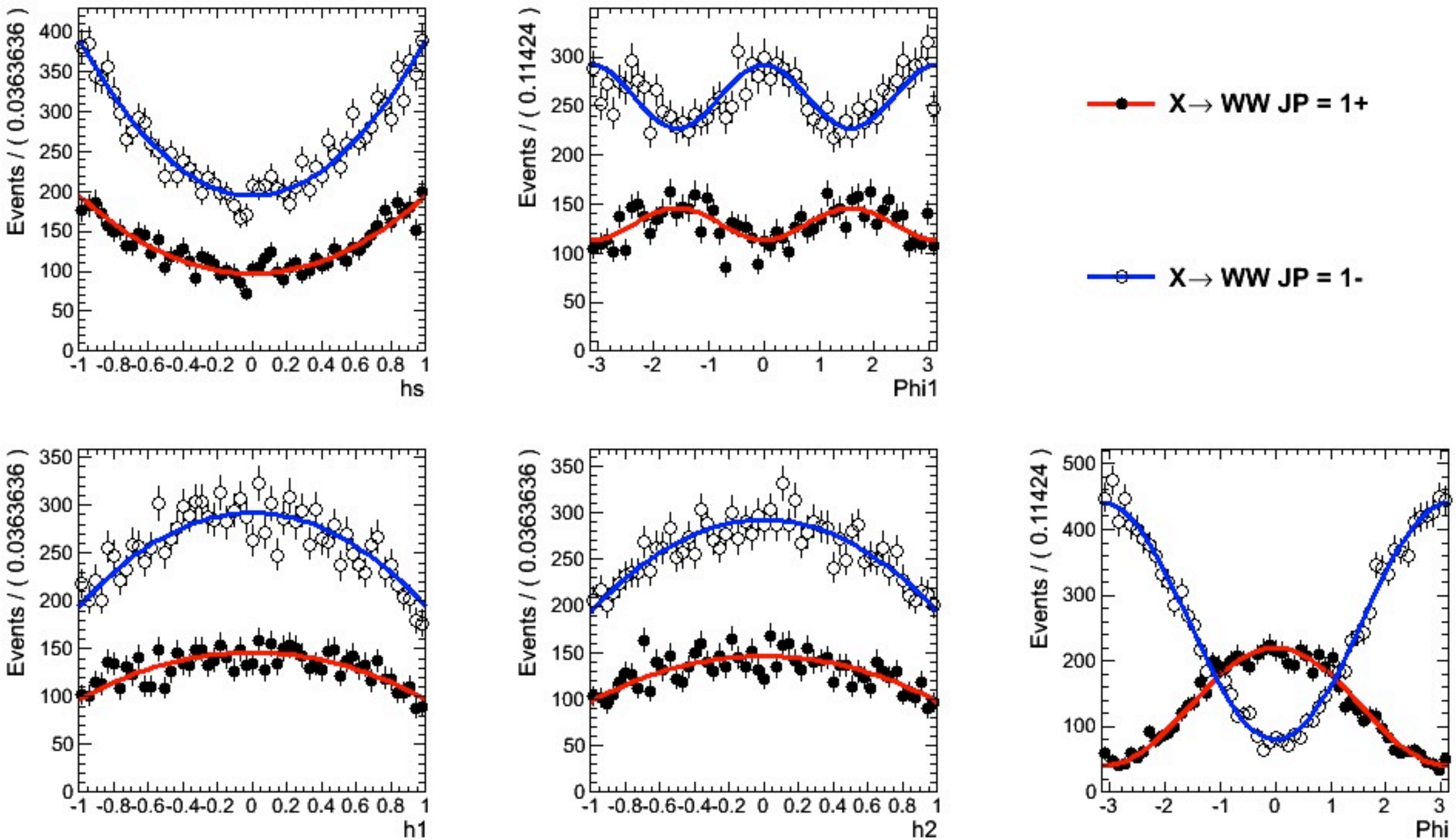
Generator Validation (X→WW Spin 0)

- In this test mX = 250 GeV



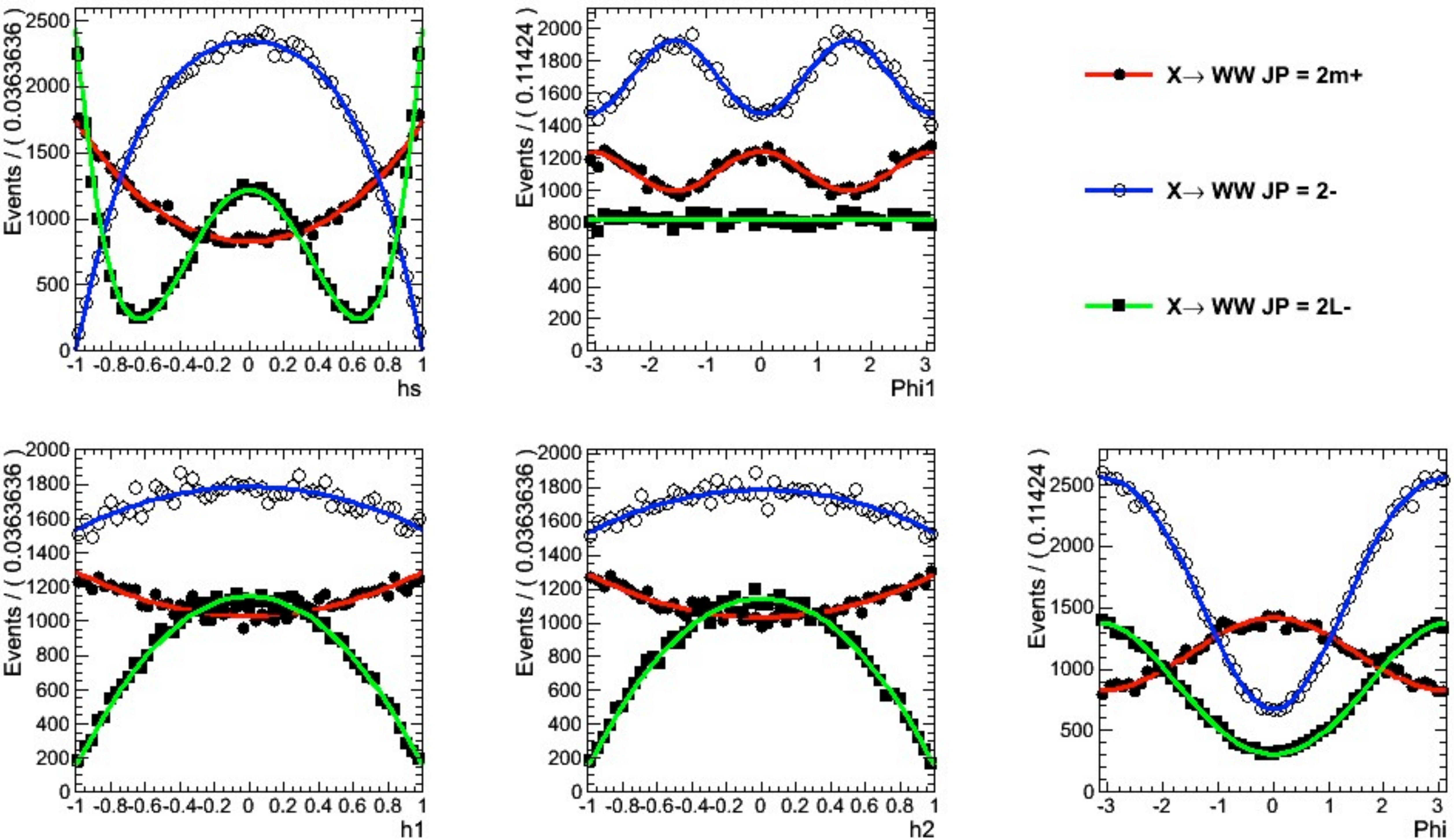
Generator Validation (X→WW Spin 1)

- In this test mX = 250 GeV



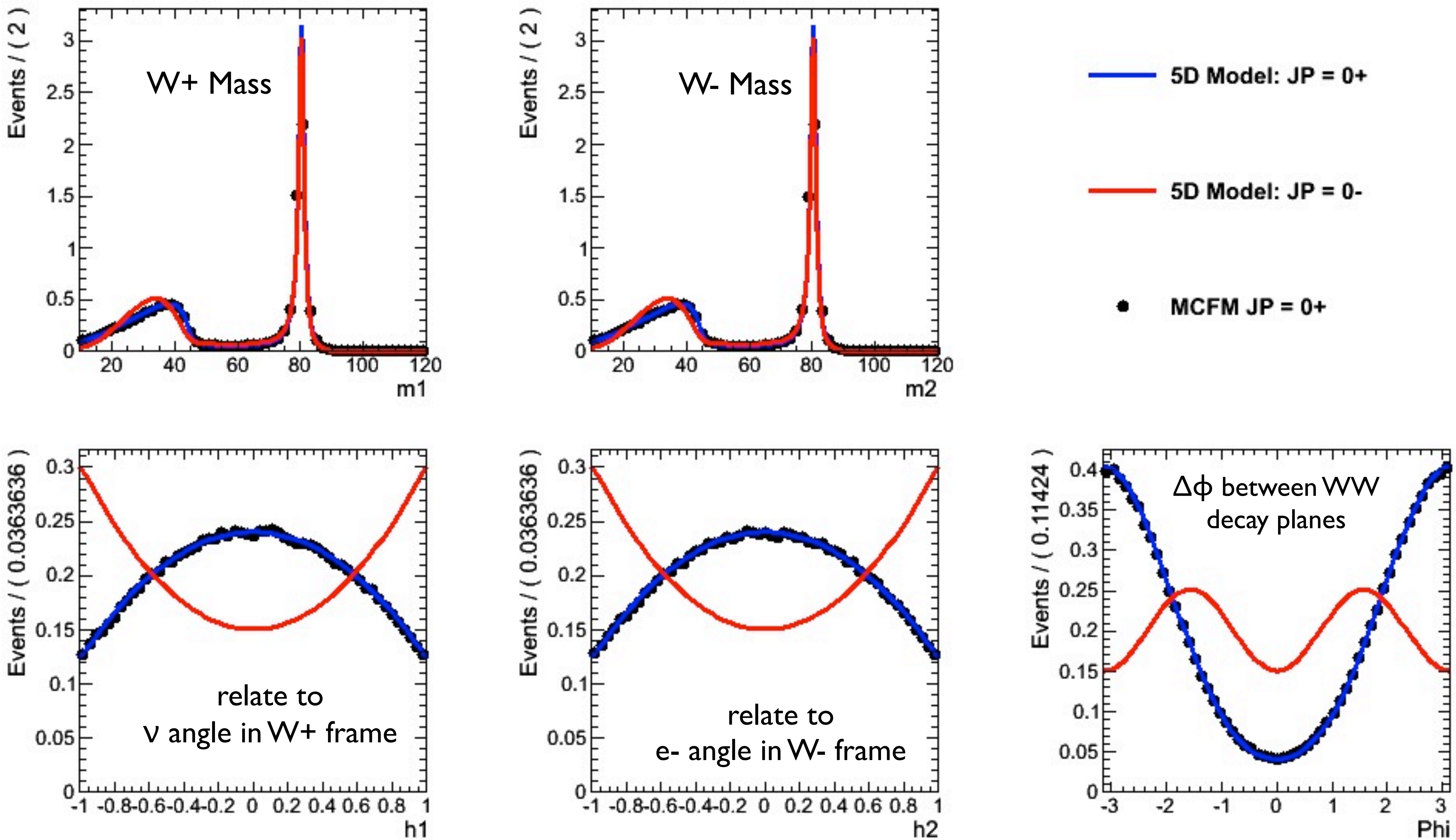
Generator Validation (X→WW Spin 2)

- In this validation, mX = 250 GeV



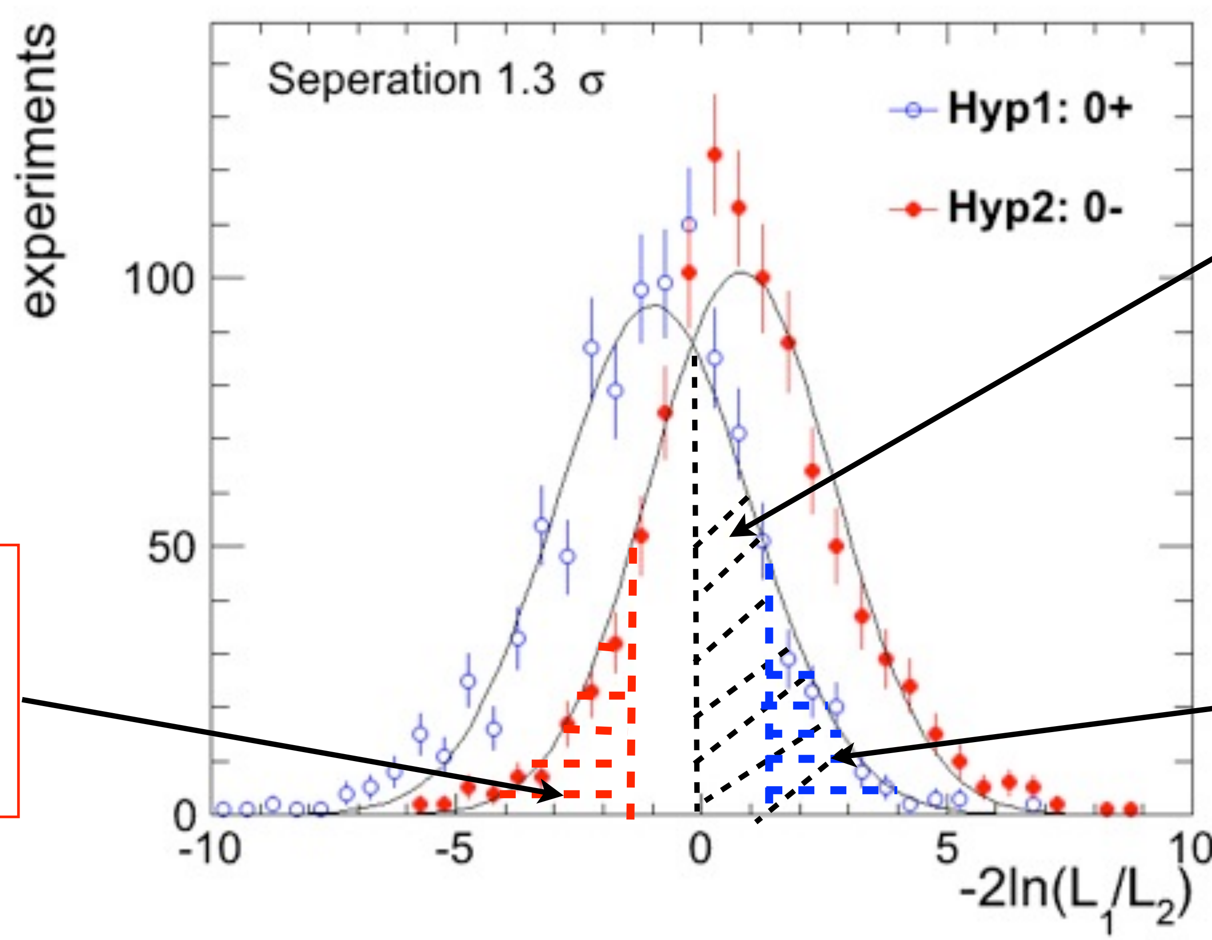
Generator Validation (SM Higgs 125 GeV MCFM)

- In this test mX = 125 GeV



Extract the hypothesis separation

- With a given dataset we calculate -2ln(L1/L2), where L1/L2 are the fitted maximum likelihood based on the S1+B and S2+B templates
- We study -2ln(L1/L2) for two sets of toy MCs generated with the two hypotheses independently, based on N toy experiments
- The exact separation depends on the interpretation
  - If the -2ln(L1/L2) are gaussian distributed, the "separation" corresponds to the separation between the peaks of the two distributions



1) Average Separation (S)
This area correspond to the one-sided Gaussian probability outside the S/2σ range

2) S_1
This quantifies the probability of Hyp1 faking the Hyp2

3) S_2
This quantifies the probability of Hyp2 faking the Hyp1